A Broad–Band Microseismometer for Planetary Applications

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Extended Abstract

There has recently been renewed interest in the development of instrumentation for making measurements on the surface of Mars. This is due to the Mars Environmental Survey (MESUR) Mission, for which ~16 small, long–lived (2–10 years), relatively inexpensive surface stations will be deployed in a planet–wide network. This will allow the investigation of processes (such as seismology and meteorology) which require the simultaneous measurement of phenomena at many widely spaced locations on the surface over a considerable length of time. Due to the large number of vehicles involved, the mass, power, and cost of the payload will be severely constrained. A seismometer has been identified as one of the highest priority instruments in the MESUR straw–man payload [1].

The requirements for an effective seismic experiment on Mars place a number of constraints on any viable sensor design. First, a large number of sensors must be deployed in a long–lived global network in order to be able to locate many events reliably, provide good spatial sampling of the interior, and increase the probability of seismic detection in the event of localized seismicity and/or high attenuation. From a practical standpoint, this means that individual surface stations will necessarily be constrained in terms of cost, mass, and power. Landing and thermal control systems will probably be simple, in order to minimize cost, resulting in large impact accelerations and wide daily and seasonal thermal swings.

The level of seismic noise will determine the maximum usable sensitivity for a seismometer. Unfortunately, the ambient seismic noise level for Mars is not well known. However lunar seismic noise levels are several orders of magnitude below that of the Earth. Sensitivities on the order of 10^{-11} g over a bandwidth of .04 to 20 Hz are thought to be necessary to fulfill the science objectives for a seismometer placed on the Martian surface [2].

Silicon micromachined sensor technology offers techniques for the fabrication of monolithic, robust, compact, low power and mass accelerometers. Conventional micro–machined accelerometers have been developed and are commercially available for high frequency and large acceleration measurements [3]. The new seismometer we are developing incorporates certain principles of conventional silicon micromachined accelerometer technology. However, currently available silicon micromachined sensors offer inadequate sensitivity and bandwidth for the Mars seismometer application. Our implementation of an advanced silicon micromachined seismometer is based on principles recently developed at JPL for high–sensitivity position sensor technology. The implementation of currently available silicon micro–machining technology with these new principles should enable the fabrication of a 10^{-11} g sensitivity seismometer with a bandwidth of at least 0.01 to 20 Hz. The addition of force–rebalance feedback control to this device will enable the dynamic range to be extended by selecting sensitivity ranges over several orders of magnitude. The low Q properties of pure single–crystal silicon also allow the system to be designed with an extremely low mechanical damping coefficient, which is necessary in order to minimize the Brownian thermal noise limitations generally characteristic of seismometers with small proof masses [4]. The total volume of the seismometer is expected to be approximately 50 cm^3 with a 50 gm total mass and power consumption of 20 mW. This will include both the sensor element and the sensor and feedback electronics.

A seismometer consists of a spring–supported proof mass (with damping) and a position sensor for measuring the displacement of the proof mass relative to the support structure. The spring–proof mass system is characterized by a natural frequency

$$\omega_0 = \sqrt{\frac{k}{m}} \qquad (1)$$

where k is the spring constant and m is the magnitude of the proof mass. For frequencies below this natural frequency, the displacement of the proof mass, x_p, is given by

$$x_p = \frac{a_s}{\omega_0^2} \qquad (2)$$

where a_s is the acceleration of the support structure. Thus in this frequency range the mechanical system acts as an acceleration–to–displacement transducer, with

$$a_s = x_p \omega_0^2 = \frac{x_p k}{m} \tag{3}$$

where a_s and x_p are now the acceleration and displacement sensitivity of the position sensor (i.e., the minimum resolvable acceleration and displacement). The output of the position sensor thus serves as a measure of the acceleration of the support structure. For a given sensitivity of the position sensor, (3) indicates that the acceleration sensitivity of the device can be improved by reducing ω_0 either by softening the support spring or by increasing the proof mass. Reducing the natural frequency, however, reduces the bandwidth of the seismometer. Thus, the increase in sensitivity is gained at the expense of frequency response. Another drawback of a low natural frequency is that it makes the system quite fragile and susceptible to damage from large accelerations. This adds considerable complexity to the mechanical system to improve its ability to withstand shocks during transport.

A more attractive method for improving the acceleration sensitivity of an instrument is to increase the sensitivity of the position sensor. In this case, a mechanical system with a higher resonant frequency (or stiffer suspension) can be used, leading to a wider operating bandwidth and insensitivity to physical shock. Thus the proof mass can be decreased, which will reduce the total instrument mass.

We have implemented this concept using a new type of high resolution capacitive position sensor and a single crystal silicon mechanical suspension. Our prototype sensor shows an acceleration sensitivity of approximately 10^{-9} g$\sqrt{Hz}$ over a bandwidth extending from 0.1 to 40 Hz. The device has a mass of under 120 gm and a volume of less than 100 cm^3. It is well suited for measurement of local seismic events, as demonstrated through field testing.

We have developed an ultrasensitive capacitive position sensor for use in a small seismometer. The important characteristics of the position sensor are: 1) it provides a position sensitivity of better than 10^{-3} A$\sqrt{Hz}$; 2) it has a wide operating bandwidth, including long term stability; 3) it has a small mass, volume, and power consumption; and 4) it is robust. In this position sensor, a grounded electrode of surface area of approximately 0.25 to 1.0 cm^2 is positioned near an electrode on the capacitance sensor. Variations in the relative spacing between these electrodes lead to changes in output from the high-frequency capacitance sensor.

A single-crystal silicon rectangular cantilever of dimensions $6 \times 30 \times 0.15$ mm is used as the spring for our seismometer. The silicon spring is cut from a larger wafer using a diamond saw. The cantilever is fixed at one end to the bottom of an aluminum support plate, using a 0.15 mm thick silicon spacer and an epoxy adhesive. A $10 \times 10 \times 3.8$ mm copper block is attached to the free end of the cantilever. This 3.4 gm block serves as both the proof mass and as one electrode for the capacitive position sensor. The static gap between the copper block and the electrode on the capacitive sensor can be adjusted sufficiently accurately using a fine-thread adjustment screw. The silicon spring has a spring constant of approximately 215 Nt/m in the vertical direction (force applied to the center of the proof mass and normal to its face). The large ratio of width to thickness of the spring gives a cross-axis sensitivity of less than 0.1%. The resonant frequency of the system in the vertical mode is approximately 40 Hz, and the mechanical Q is greater than 400 in air. This high Q value is essential for a low mass seismometer, as it reduces the thermal noise equivalent acceleration of the device, which for the present instrument is approximately 2.2×10^{-10} g$\sqrt{Hz}$.

Initial tests of the first microseismometer show that a very small, low-mass instrument using conceptually simple detection techniques can exhibit performance comparable to state-of-the-art instruments. This is an important result in the development of miniature seismic instrumentation for terrestrial, as well as planetary seismology.

[1] Mars Science Working Group, A Strategy for the Scientific Exploration of Mars, JPL D-8211 (Internal Document), Jet Propulsion Laboratory, 1991.
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